Renovation of the Photovoltaic-Diesel Generator
System at
Natural Bridges National Monument

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# Abstract

Renovation of the Photovoltaic-Diesel Generator Hybrid System at Natural Bridges
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In 1979 a large 93 kW photovoltaic-diesel generator hybrid system was
installed as the only source of power for Natural Bridges National
Monument.  As the components in the system have aged the performance
of the system has declined by more than 50% despite its upgrade in
1992.  Natural Bridges has enlisted the help of the Federal Energy
Management Program (FEMP) to provide suggestions on how to
upgrade the existing hybrid system.  A software program called Hybrid
Optimization Model for Electric Renewables (HOMER) was used in
determining cost-effective measures of upgrading the existing hybrid
system at Natural Bridges.  Two primary simulations were modeled in
HOMER:  the existing hybrid system performance and the optimum
upgraded system.  The model of the existing hybrid system was found to
closely match the performance of the actual system.  The HOMER
simulations determined the optimum upgraded system to have a 40 kW
photovoltaic array, a 400 kWh battery bank, a 40 kW inverter, and the
current 60 kW generator.  Based on knowledge of the condition of the
components within the system and HOMER simulations, FEMP made
recommendations to maintain the existing 40 kW photovoltaic array as
well as the 60 kW generator, replace the existing 500 kWh battery bank
with a 400 kWh battery bank, and also to replace the existing 50 kW
inverter with a newer model.

**Introduction**

  In the late 1970's photovoltaic technologies were rapidly expanding in an era of

expensive fossil fuels.  However, many people were unaware of photovoltaics and how these

technologies could be used to solve some of our energy needs.  In order to educate the general

public about the basics of photovoltaics and their uses, certain places throughout the US were

chosen as demonstration sites.  On these sites, photovoltaic systems were installed with the goal

of meeting most of the energy needs for the facilities on each site.  Natural Bridges National

Monument was chosen as one of these demonstration sites.

  Natural Bridges National Monument was chosen as a photovoltaic demonstration site for

a number of reasons.  First, located in Utah's southeastern desert, Natural Bridges' climate is

ideal for solar energy since it is sunny, yet moderate.  Also, Natural Bridges is located far from

commercial power sources and extending the power lines would have been an expensive process

(National Park Service, n.d.).

  Prior to the installation of the photovoltaic system, power to Natural Bridges was

supplied solely by a diesel generator.  The current photovoltaic and diesel generator hybrid

system continues to be the only source of power available for Natural Bridges.

  Over time, the photovoltaic system at Natural Bridges has begun to decline.  Although

the system was upgraded in September 1992, the PV array continues to output at less than 50%

of its original output in 1979 (Southwest Technology Development Institute, 1998).   Yet, even

at this decreased output of 42 kW or 260 kWh/day, the PV array still meets the majority of the

site loads at Natural Bridges, which average 285 kWh/day.

  The purpose of this project submitted to the Federal Energy Management Program

(FEMP) was to evaluate the existing photovoltaic and diesel generator hybrid system using a

software program called Hybrid Optimization Model for Electric Renewables (HOMER). The HOMER program was used to determine the best components of the system to upgrade based on cost and fuel use.


**Materials and Methods**

HOMER assists researchers in designing an optimal hybrid power system based on comparative economic analysis. The HOMER software determines optimal hybrid systems using combinations of photovoltaics, wind turbines, micro-hydro, biomass, diesel generation, battery storage, and inverter capacity. HOMER also takes into account both seasonal and hourly load variations as well as variations in resource availability such as wind and sunlight (Lilienthal, 2001). In addition, HOMER outputs multiple options ranked in order of least net present cost, which is based on a 20-yr lifecycle cost including interest. For the purposes of upgrading the system at Natural Bridges, the options to include wind turbines, micro-hydro, and biomass were discounted as these are poor resources at Natural Bridges.

HOMER is most widely used for designing and sizing hybrid systems that do not yet exist. However, at Natural Bridges, a hybrid system already exists. In order to take into account the productivity of the existing system, the inputs into HOMER were altered.

For the purposes of this project, HOMER was used to model two different types of systems for different purposes. The first system modeled in HOMER was created to perform similarly to the existing system at Natural Bridges. The inputs into HOMER were based on historical data and performance. The output of greatest importance was the diesel generator fuel usage, which was compared to the actual fuel usage. This comparison of the modeled fuel usage and the actual fuel usage helped to create confidence in HOMER as a modeling tool. The goal of

the second system modeled in HOMER was to determine the optimum upgraded system, taking into account the functional components of the already existing system. Further details about the differences in inputs to model these two systems are revealed below.

*Load Inputs*

Load data from Natural Bridges was acquired from various sources. First, historical load data was analyzed, collected on a monthly basis from 1995 until February 2000. The plot of the average load per month for this time period over the year revealed that there exists little variation in seasonal loads (Figure 1). Also, based on this data, the average load was calculated to be 209 kWh/day. This average load was used while modeling the existing system performance in HOMER.

Current load data was more difficult to obtain since Natural Bridges discontinued recording their monthly load use after February 2000. However, a data logger was used to obtain current load data beginning June 20, 2001 and ending July 5, 2001. From this data, the average load was calculated as 285 kWh/day, which signals a large load growth over the past two years. According to Joe Joliet at Natural Bridges, this load growth is justified by the addition of two electric dryers, several computers, a new maintenance shop, a new residence, and more employees during the past two years. This increased load was confirmed again by daily onsite meter readings which were also recorded during the same time period. The data logger also recorded peak loads throughout the day which typically were in a range of 30-35 kVA (Figure 2). The average load and peak loads obtained from the data logger were used while modeling the optimum upgraded system in HOMER.

The load data from the logger was also used to establish a daily load profile. The logger read information about average kWh for every 5 minutes, which was used to determine the average load for every hour of the day. An actual daily load profile was generated based on this data (Figure 3), but the profile was modified slightly when input into the HOMER program (Figure 4). This modified daily load profile was used in HOMER to model both the existing system and the optimum upgraded system. The loads per hour in the profile for the existing system model were proportionally scaled down in HOMER to meet the lower load of 209 kWh/day.

*Resources*

The solar resource data for Cedar City, Utah was input into the HOMER model. This data was obtained from a directory that contains data files for the typical meteorological year (TMY) for a given location. The TMY for Cedar City was derived from the 1961-1990 National Solar Radiation Data Base (Marion and Urban, 1995). Cedar City is one of the closest cities to Natural Bridges which has this solar resource data and was chosen over some other nearby cities, such as Grand Junction, based on elevation, latitude, and general knowledge of weather patterns.

*Photovoltaic Components*

The photovoltaic (PV) array was input into HOMER as being non-tracking, having a slope of 41°, and facing directly south. The lifetime of the array was assumed to be 20 years.

When modeling the performance of the existing hybrid system, the PV was assumed to have an output of 45 kW. This value is higher than the current true PV output, but it was used instead since the PV had previously performed at this output during the same time period of the

collected data.  In general, the data used to model the existing performance of the hybrid system was acquired two or more years prior to today.  Likewise, the actual generator fuel use, which was compared to the HOMER modeled fuel use, was also based on data from two or more years ago.  At this point in time, the PV had an output of 45 kW.

When modeling the optimum upgraded system, the PV was input as having a capacity of 40 kW, which is very close to its current measured output.  In order to simulate that the system could already provide 40 kW from the PV, the capital cost was input as $0.  However, the cost of adding 1 kW of PV, making the total output of the array 41 kW, was input as having a capital cost of $7,000 with an operation and maintenance cost of $10 per kW/year (Figure 5).  HOMER was also given options to choose from for PV array size so that it could determine the optimum array size.  These options began at 0 kW continuing on in increments of 5 kW up to 65 kW.

*Genset*

Natural Bridges is currently using a 60 kW primary generator with a 30 kW generator as a back-up.  For the purposes of modeling this system in HOMER, the existence of a 60 kW generator was solely noted .   In order to account for the existing 60 kW generator, the capital cost of 60 kW was assumed to be $0.  However, an additional 60 kW generator, which would make the total capacity 120 kW, was input as costing $15,000 (Figure 6).  The operation and maintenance costs for the generator were input as $ ____  per generator run hours.  The fuel price was set at $0.4/L, which was equal to the last price Natural Bridges paid for diesel fuel in February 2001.  For additional inputs into the Genset component, see Figure 6.  When determining the optimum upgraded system, HOMER was given the option to choose from a 60 kW, a 99 kW, or a120 kW sized generator.

*Battery*

For both models simulated in HOMER, a C&D CPV 1550 battery was input. This battery was chosen based on a phone conversation with Joe Joliet at Natural Bridges, who stated that they have been planning on replacing the current batteries with this model. The capital cost of $526 for 3 kWh was also determined from Joe Joliet, who had been quoted a purchase price from a C&D representative of $120,000 for 228 cells and corresponding racks. The operation and maintenance cost for a 3 kWh battery was estimated to be $8/year. Since Natural Bridges desired to replace their existing batteries with the C&D CPV 1550 batteries, this model was chosen as an input to model the optimum upgraded system. This battery model was also chosen to simulate the existing hybrid system performance since the current batteries, C&D QP160-23 have a similar performance. When determining the optimum upgraded system, HOMER was given the option to different battery bank sizes ranging from 0 kWh in increments of 50 kWh up to 800 kWh. For additional battery inputs, see Figure 7.

*Inverter*

Currently a 50 kW Cyberex inverter is being used in the existing hybrid system. However, this inverter was installed in 1979 and has a much lower efficiency of 70% than modern inverters which typically have an efficiency of 85% (Figure 8). These values are reflected in the HOMER inputs when modeling the performance of the existing system.

When modeling the optimum upgraded hybrid system in HOMER, it was assumed that a new inverter would be used. The current inverter is very old and difficult to service and obtain replacement parts. The maintenance staff at Natural Bridges wishes to replace the inverter in the

immediate future.  As a result, the model for this simulation assumes a new 50 kW inverter with 85% efficiency will be purchased for a capital cost of $50,000, having an operation and maintenance cost of $300/yr (Figure 9).  Furthermore, HOMER was given options to choose for the size of the inverter.  These options were 40 kW, 50kW, and 60 kW.  HOMER was not given an option to choose an inverter smaller than 40 kW due to the daily peak loads which tend to exceed 30 kW regularly (Figure 2).

**Results**

One of the first goals in analyzing the hybrid system at Natural Bridges was to correctly model the existing system performance.  In this model, the HOMER inputs were set to model the hybrid system performance prior to 2000, assuming a load of 209 kWh/day, a 45 kW PV array, a 60 kW generator, and a 50 kW inverter with 70% efficiency.  The existing battery bank has a reported 500 kWh capacity, but was input into the model as having only 400 kWh, due to the age and degradation of the bank over time.   Based on these inputs, HOMER predicted a generator fuel use of 12,510 L/yr in optimal conditions (Table 1).  This value compares closely to the actual fuel use at Natural Bridges from 1996-1999, which was 14,100 L/yr on average.  The higher value of the actual fuel use compared to the HOMER predicted fuel use can be accounted for in the fact that the system cannot perform optimally at all times.  Yet, HOMER assumes these optimal conditions.  The ability to model the existing system performance in HOMER to yield results that match its actual performance demonstrates the accuracy of the HOMER modeling program.

The second goal of analyzing the hybrid system at Natural Bridges was to determine an optimum upgraded system.  Taking into account the functional components of the existing

system, the HOMER simulation calculated that the upgraded system with the lowest net present cost would contain the current 40 kW PV array, the current 60 kW diesel generator, a smaller battery bank with a capacity of 400 kWh, and a 40 kW inverter. HOMER estimated the fuel use for this system to be 20.073L/year with 1655 generator run hours per year (Table 2). Furthermore, HOMER determined the total capital cost for this system to be $110,133 and the total net present cost to be $511,217. Currently at Natural Bridges, a 538 kWh battery bank is in place and the staff that maintains the system intends to replace the existing battery bank with a similar 500 kWh bank. According to HOMER calculations, this 100 kWh increase in battery bank size from 400 kWh to 500 kWh would increase the capital cost by more than ___% and would also increase the total net present cost by more than ____ %, while only reducing fuel use by ___% per year (Table 2).

An additional HOMER simulation was performed in order to model the hybrid system at Natural Bridges if the system were allowed to continue to degrade. In this case, the inverter and battery bank would cease to function within a short period of time, causing the PV array to become disconnected from the system so that it no longer provides power. As a result, the existing 60 kW generator would be the only source of power for Natural Bridges. HOMER estimated that, in this case, the generator would run for 8,759 hours/year and use 45,260 L/yr of fuel which is more than double the amount of fuel use predicted in the optimized model (Table 3). At the current price of $.40/L for diesel fuel this estimated fuel use would cost Natural Bridges approximately $18,800/year. The net present cost predicted by HOMER for this project would exceed $621,500.

Another HOMER simulation was also performed to determine an optimized system if a penalty for emissions was implemented. This penalty was assumed to be $0.44/L of diesel fuel

(how did we get this value???), more than doubling the cost of fuel from $0.40/L to $0.84/L. However, this emission penalty did not change the optimized system determined by HOMER. For more detailed results please refer to Table 4.

**Discussion and Conclusions**

Based on the results of the various HOMER simulations, the following recommendations have been presented to the staff at Natural Bridges and the Southeast Utah NPS group.

First, FEMP proposed several general recommendations about the hybrid system. The staff at Natural Bridges should try to slow or reverse their load growth by such methods as using Energy Star appliances, replacing electric dryers with gas dryers, and increasing new staff awareness of the unique energy situation at Natural Bridges. Decreasing the load will lessen the use of the generator and therefore the consumption of diesel fuel. In addition, Natural Bridges should maintain their existing 40 kW PV array size as there are few economic benefits in increasing the array output (Table 5). However, FEMP does recommend replacing the battery bank and the inverter in the system.

FEMP advised replacing the existing inverter with a new 40-50 kW inverter. The size of the inverter is based on the daily peak loads, which tend to meet or exceed 35 kW regularly. While a 40 kW inverter is an acceptable size for the existing system, this size inverter is rarely manufactured compared to 50 kW inverters. However, a 40 kW inverter may be preferred if the loads at Natural Bridges remain low since an oversized inverter decreases the efficiency of the system. The specific inverter recommended was an Advanced Energy System (AES) Model SPP50 with a split-phase 120/240 V AC output. An AES model was chosen over Trace Technologies models due to the fact that Trace does not currently manufacture a split-phase

120/240 V AC inverter.  Furthermore, a similar inverter is currently being installed at the Maze in Canyonlands, which is managed by the same National Parks System (NPS) regional office as Natural Bridges.  Installing a similar inverter in Natural Bridges and in Canyonlands could offer the Southeast Utah NPS group many maintenance benefits by having similar equipment and the same software.

FEMP also recommended replacing the existing 538 kWh, 230V DC battery bank with a new 240 V DC battery bank of approximately 400 kWh in size.  The cells in the existing battery bank are near the end of their life and should be replaced soon.  The change from 230 V DC to 240 V DC is necessary to meet current industry standards for inverters.  The suggestion to downsize the battery bank was derived from the results of the HOMER simulations, which determined that the system does not need a battery bank much larger than 400 kWh.  FEMP has proposed installing two parallel strings of 2 V cells with 120 cells per string.  More specifically, FEMP recommended using one of the following two models of cells:  C&D CPV 890 which would yield 418 kWh or C&D CPV 1000 which would yield 470 kWh.

In addition, FEMP also recommended replacing the Master Control Center at Natural Bridges.  This Master Control Center is a computer more than 20 years in age, which requires high maintenance, and contains little or no replacement parts.  FEMP proposed replacing this control center with a new AES charge controller which has a 9 channel last stage pulse width modulation (PWM).  The existing Master Control Center has a complicated 48-step relay and an Uninterruptible Power Supply (UPS).  Replacing this Master Control Center would eliminate an unnecessary computer and UPS.

**Acknowledgements**

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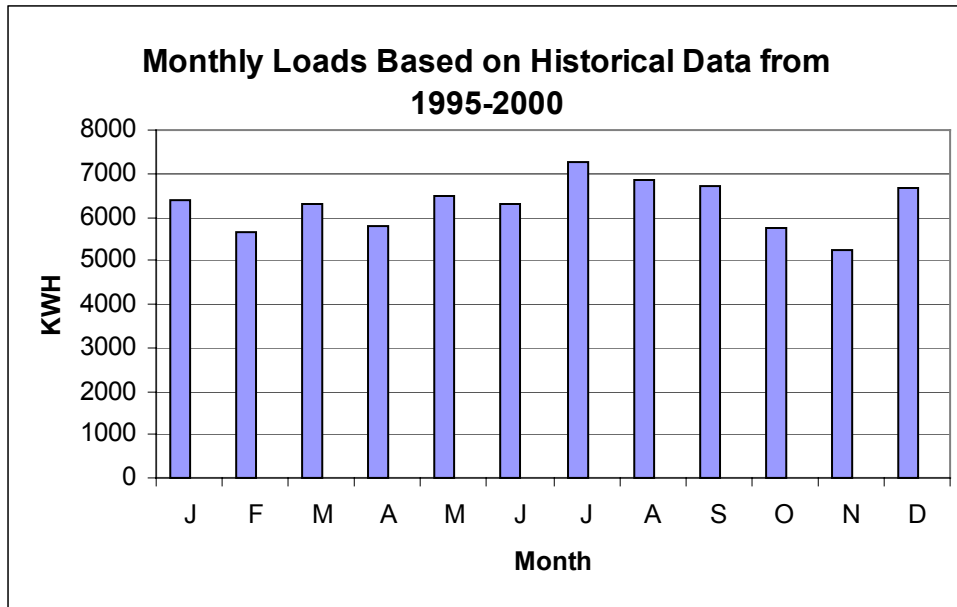
Figure 1.  Monthly loads based on historical data from 1995-2000.
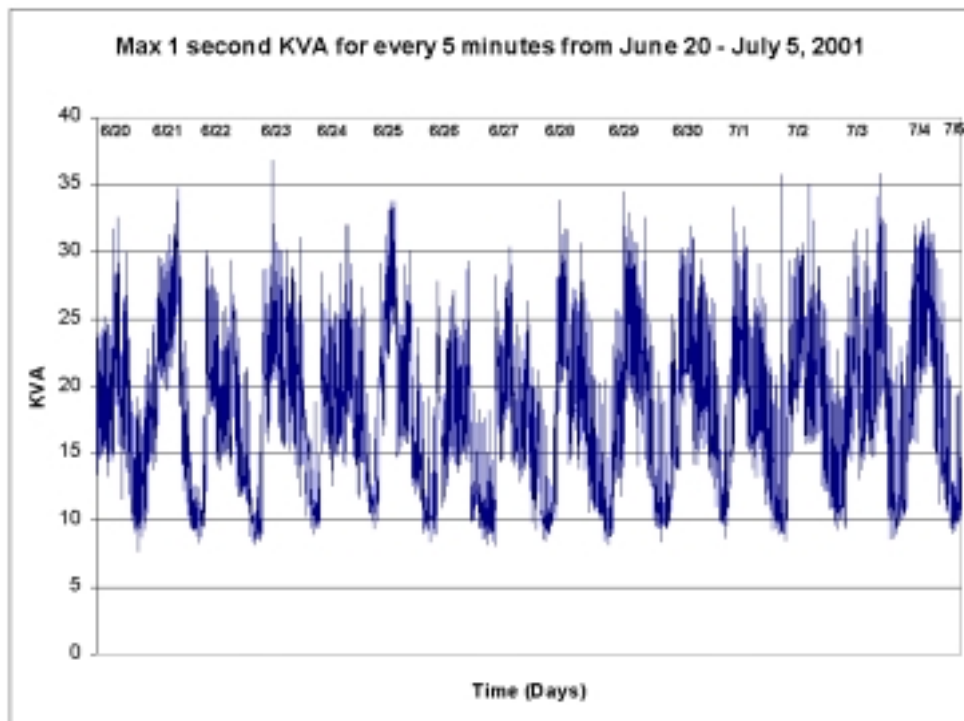


Figure 2.  Max 1-second kVA for every 5 minutes from June 20 - July 5, 2001.
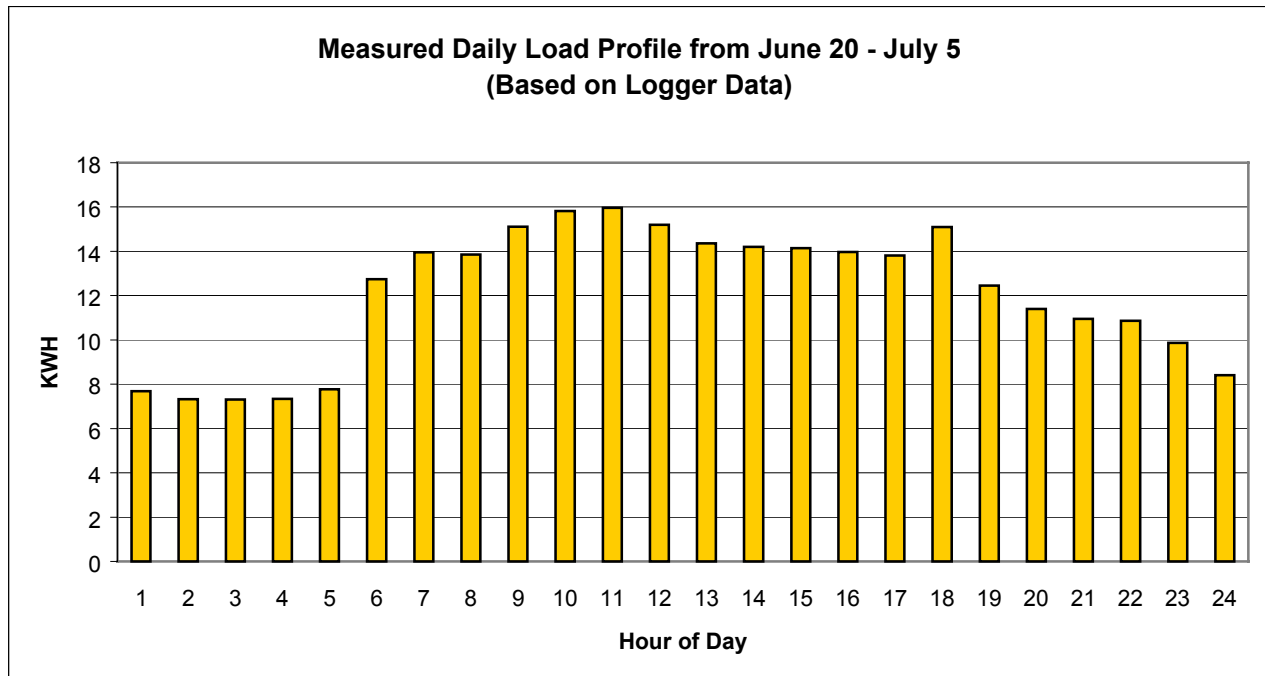
Figure 3.  Measured daily load profile based on recordings from the data logger during June 20 - July 5, 2001.
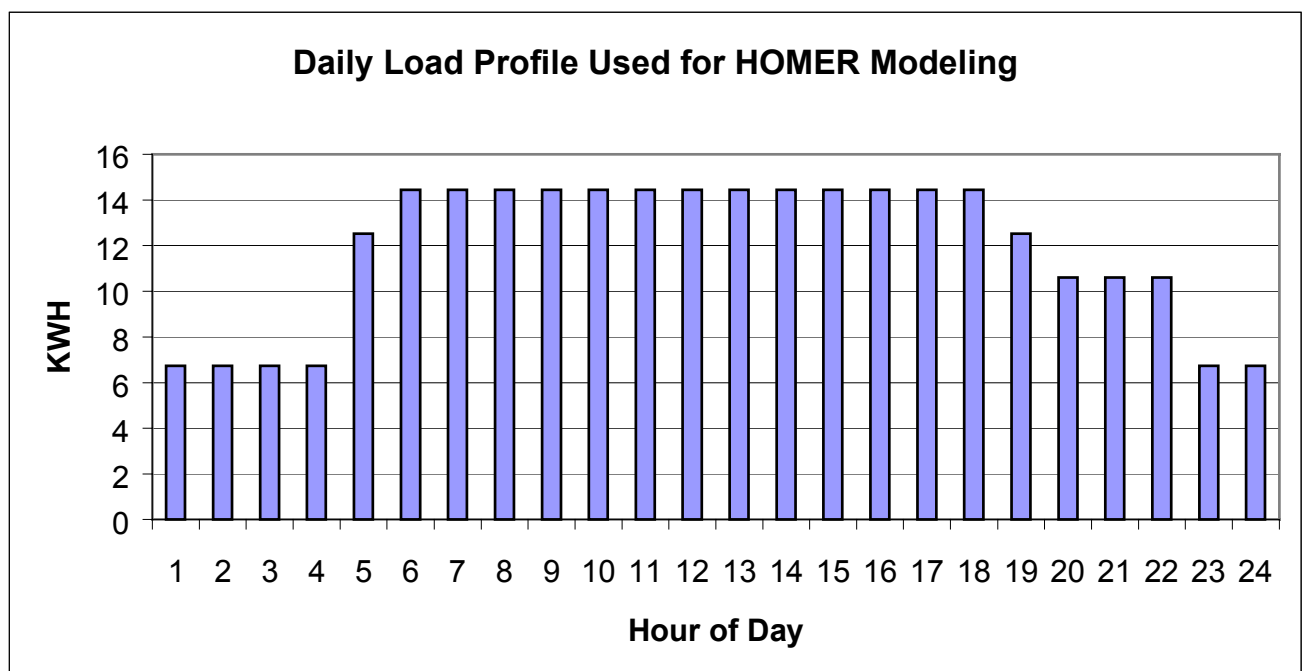


Figure 4.  Daily load profile used for HOMER modeling.

Figure 5. A screen shot from the PV component inputs in HOMER.



Figure 6. A screen shot from the genset component inputs in HOMER.

Figure 7.  A screenshot from the battery component inputs in HOMER.
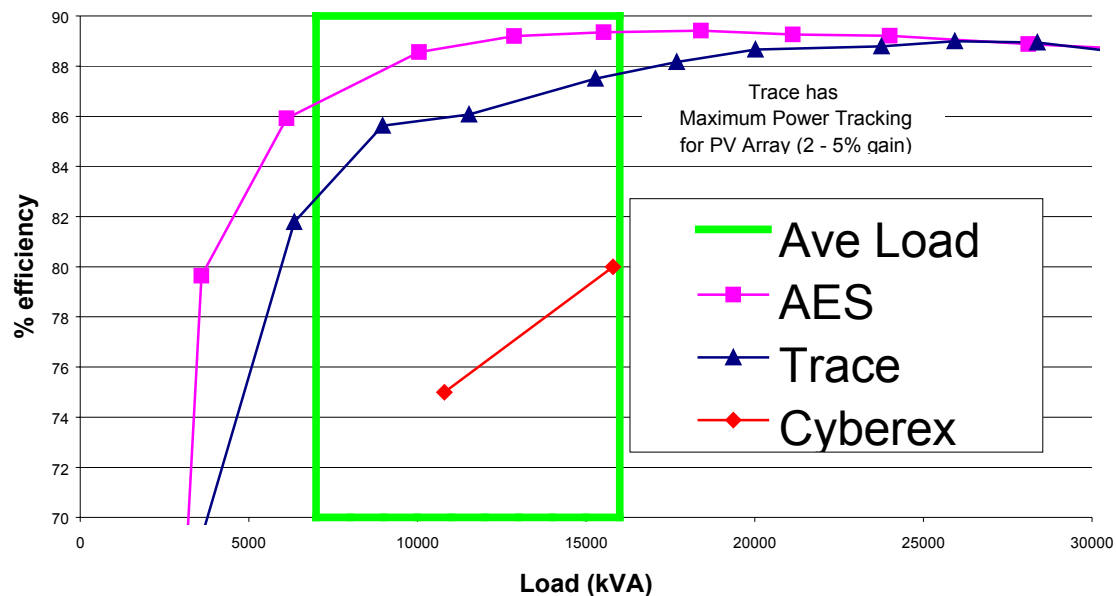


Figure 8.  Measurements of the efficiency of inverters compared to the load.  Graph obtained from Mark Ralph at Sandia National Laboratory, Albuquerque, New Mexico.

Figure 9. A screen shot of the inverter inputs in HOMER.

Table 1. Results from modeling the existing hybrid system at Natural Bridges with HOMER.

| Component | Size |
|---|---|
| PV (kW) | 45 |
| Generator (kW) | 60 |
| Battery (kWh) | 400 |
| Inverter (kW) | 50 |
| Fuel Consumption (L/yr) | 12510 |
| Generator Hours (hr/yr) | 1064 |

Table 2.  Results from modeling the optimum upgraded hybrid system at Natural Bridges with HOMER.

| Component | Optimum | Optimum with 500 kWh batteries |
|---|---|---|
| PV (kW) | 40 | 40 |
| Generator (kW) | 60 | 60 |
| Battery (kWh) | 400 | 500 |
| Inverter (kW) | 40 | 40 |
| Fuel Consumption (L/yr) | 20,073 | 19,990 |
| Generator Hours (hr/yr) | 1165 | 1457 |
| Capital Cost | $110,133 | |
| Net Present Cost | $484,315 | |

Table 3.  Results from modeling a generator-only system at Natural Bridges with HOMER.

| Component | Size |
|---|---|
| PV (kW) | 0 |
| Generator (kW) | 60 |
| Battery (kWh) | 0 |
| Inverter (kW) | 0 |
| Fuel Consumption (L/yr) | 45,260 |
| Generator Hours (hr/yr) | 8759 |
| Capital Cost | $ |
| Net Present Cost | $ |

Table 4.  Results from modeling an emissions penalty in the cost of fuel for the system at Natural Bridges using HOMER.

| Component | Optimum |
|---|---|
| PV (kW) | 40 |
| Generator (kW) | 60 |
| Battery (kWh) | 400 |
| Inverter (kW) | 40 |
| Fuel Consumption (L/yr) | 20,073 |
| Generator Hours (hr/yr) | 1165 |
| Capital Cost | $110,133 |
| Net Present Cost | $ |

Table 5. Results from modeling the addition of 5 kW PV and 10 kW PV at the system at Natural Bridges using HOMER.

| Component | Adding 5 kW PV | Adding 10 kW PV |
|---|---|---|
| PV (kW) | 45 | 50 |
| Generator (kW) | 60 | 60 |
| Battery (kWh) | 400 | 400 |
| Inverter (kW) | 40 | 40 |
| Fuel Consumption (L/yr) | 17,655 | 15,413 |
| Generator Hours (hr/yr) | 1165 | 1197 |
| Capital Cost | $ | |
| Net Present Cost | $ | |